

# **RESPONSE OF THE OCEANIC BOUNDARY LAYER TO WIND FORCING**

Dave Hebert

Graduate School of Oceanography

University of Rhode Island

Narragansett, RI 02882-1197

Tel: (401) 874-6610 Fax: (401) 874-6728 email: hebert@gso.uri.edu

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## **LONG-TERM GOALS**

My long-term goal is to understand small-scale mixing processes such as internal waves, double-diffusion, and intrusions and to determine their influence on the larger-scale dynamics.

## **OBJECTIVES**

Initially, for this AASERT award, Andrew Mack was going to analyze data collected on a joint Oregon State University – University of Rhode Island experiment which took place from September 22-30, 1994 at Waldo Lake, Oregon. This purpose of this experiment was to compare different microstructure-based estimates of the vertical heat flux near the ‘ocean’ surface under a range meteorological conditions. During the first year of the ASSERT award (1994-1995), while waiting for the collection of the Waldo Lake data and its subsequent calibration, Andrew was examining thermistor chain data collected in the equatorial Pacific. He had hoped to compare the mixing processes in the highly-sheared upper ocean of the equatorial Pacific to mixing processes in the ‘low-sheared’ Waldo Lake. Unfortunately, during the calibration of the Waldo Lake data, it became apparent that the noise level on some of the sensors made the dataset collected at Waldo Lake of limited use. Thus, Andrew has decided to put all of his efforts into examining the dynamics of the high-frequency waves observed in the equatorial Pacific.

Andrew has posed three hypotheses for his dissertation:

- The generation of the majority of observed waves is due to shear instabilities of the mean flow.
- The waves are important to the annual zonal-momentum and heat budgets in this region.
- Shear instability is the dominant mechanism for transferring internal-wave energy to turbulent mixing.

## **APPROACH**

These hypotheses were tested with a combination of data analysis, stability analysis and numerical modelling. High-frequency internal waves were observed for four days during an along-equator transect in 1987. Vertical profiles of salinity, temperature and turbulent kinetic energy dissipation rate were obtained approximately every kilometer. Upper ocean velocities were obtained with an ADCP. Over the top 125 m, a towed thermistor chain, with sensors spaced approximately 4 m vertically, were sampled at 20 Hz. This data was provided by Caldwell, Moum and Paulson of Oregon State University.

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Predictions of the fastest-growing waves using linear stability analysis of the observed hydrographic conditions were compared to observed wave properties.

Simulations with a large-eddy simulation (LES) model (Skylingstad and Denbo 1994) were undertaken to test the previously proposed generation mechanisms.

## WORK COMPLETED

The data analysis and model simulations have been completed. Andrew Mack successfully defended his Ph.D. thesis. One manuscript has been published and two others have been submitted.

## RESULTS

On the basis of data from a towed thermistor chain collected near 140°W on the equator during April 1987, the zonal wavenumber and vertical structure of internal gravity waves were observed to vary significantly between wave events. Our hypothesis is that this variability is due to changes in the vertical structure of mean horizontal velocity and density. Assuming that the observed waves were the fastest growing modes for shear conditions during 4 nights of intense internal wave activity. We found that while the observed waves are of finite amplitude, linear shear instability is sufficient to explain the wavelength and vertical structure of vertical displacement for most of the waves (Mack and Hebert 1997a). The fastest growing, unstable, mode-one solutions have *e*-folding growth times of less than 10 min. These solutions show wave phase speeds and vertical structures to be highly dependent upon the velocity structure of the uppermost 40 m of the mean flow.

In the past, it has been suggested that the mean zonal pressure gradient in the equatorial Pacific was balanced by the vertical divergence of the turbulent stress. Estimates (Dillon et al. 1989, Hebert et al. 1991) have found the vertical divergence of the turbulent stress too small in the upper ocean. The vertical wave-induced Reynolds stress divergence could explain a discrepancy in zonal momentum budgets of the upper 90 m of this region. Using the linear stability analysis, estimates of this stress divergence show that only about 100 days of intense internal wave activity is needed per year for these internal waves to explain estimated residuals of the mean zonal momentum budgets of this region at 50- to 100-m depth Mack and Hebert 1997a).

The thermistor chain data revealed the presence of high-frequency internal waves in the upper 125 m having zonal wavelengths of 150–250 m (Moum et al. 1992). Turbulence dissipation rates,  $\epsilon$ , observed from a free-falling profiler were high when wave packets were present. Unfortunately, the frequency of the vertical profiles of  $\epsilon$  taken did not resolve the internal wave cycle and so a dynamical link between the waves and the mixing could not be directly observed with vertical profiler data. It is presumed that either wave-induced shear instability or advective instability destabilized the waves and led to increased  $\epsilon$ . The thermistor data, which were sampled at 20 Hz or approximately 12.5 cm, was used to determine the structure of turbulence within an internal wave cycle. While the Batchelor spectrum was not completely resolved, the observed, under-estimated temperature gradient variance was used as a surrogate for  $\epsilon$ . The temperature gradient variance data were calibrated with accurately measured  $\epsilon$  from the vertical

profiler. Observations of this thermistor chain-based dissipation rate  $\epsilon_{tc}$  was examined as a function of internal wave phase and depth. A consistent structure of turbulent mixing within the wave cycle was revealed (Mack and Hebert 1997b). This structure, having relatively higher  $\epsilon_{tc}$  associated with wave crests near 20-m depth and wave troughs near 60-m depth, is consistent with purely wave-induced shear instability based on its criterion and is not consistent with purely advective instability. Estimated  $\epsilon_{tc}$  as a function of  $\bar{U}_z/\bar{N}$  ( $\bar{U}_z$  is the mean vertical shear of zonal velocity and  $\bar{N}$  is the mean buoyancy frequency) and wave slope (defined as the product of the wavenumber and the wave displacement amplitude) demonstrates that both advective and shear instability are present (Figure 1). However, the background shear and stratification are such that the vast majority of observed waves are associated with purely shear instability.

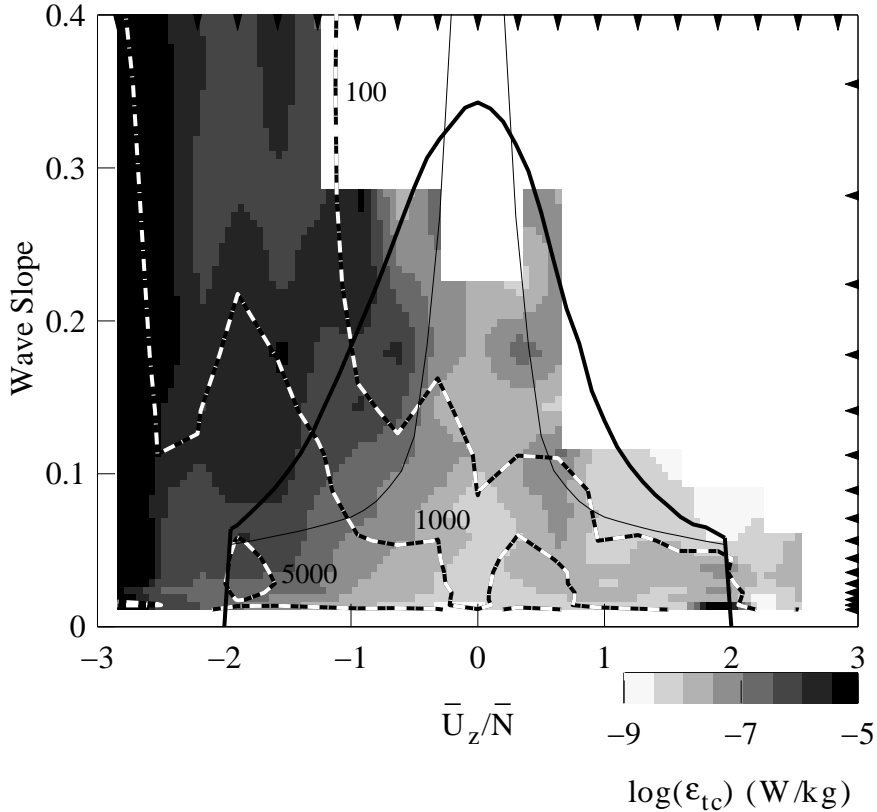


Figure 1. Average  $\epsilon_{tc}$  from all thermistors and over 4 days as a function of mean Froude number and wave slope. (The center of each averaging bin is indicated along the top and right borders. The 100, 1000, and 5000 contours (dashed lines) for the number of occurrences in each bin are shown. Bins with no occurrences are white.) The thin and thick black lines are the Couette and transition-layer stability curves, respectively (Thorpe 1978).

Two-dimensional, nonhydrostatic, Boussinesq, numerical model simulations of hydrographic conditions similar to those found in April, 1987, at 140–132°W on the equator were undertaken to investigate the generation mechanism and growth of high-frequency internal waves (Mack and Hebert 1997c). A combination of the impingement of boundary layer eddies on an underlying sheared flow, known as the obstacle effect, and shear instability of the background flow was found to generate growing internal waves (Figure 2). Wave generation occurred after sundown when surface cooling led to an unstable surface-layer temperature gradient and a buoyancy driven eddy reached the

base of the 25–35-m surface boundary layer. The eddy was advected with and gained energy from the mean shear flow. The initial boundary layer eddy excited unstable internal waves which formed downstream of the eddy and gained energy directly from the mean flow. The waves have wavelengths, phase speeds, wave displacement vertical structures, and growth rates consistent with observations and linear shear instability theory.

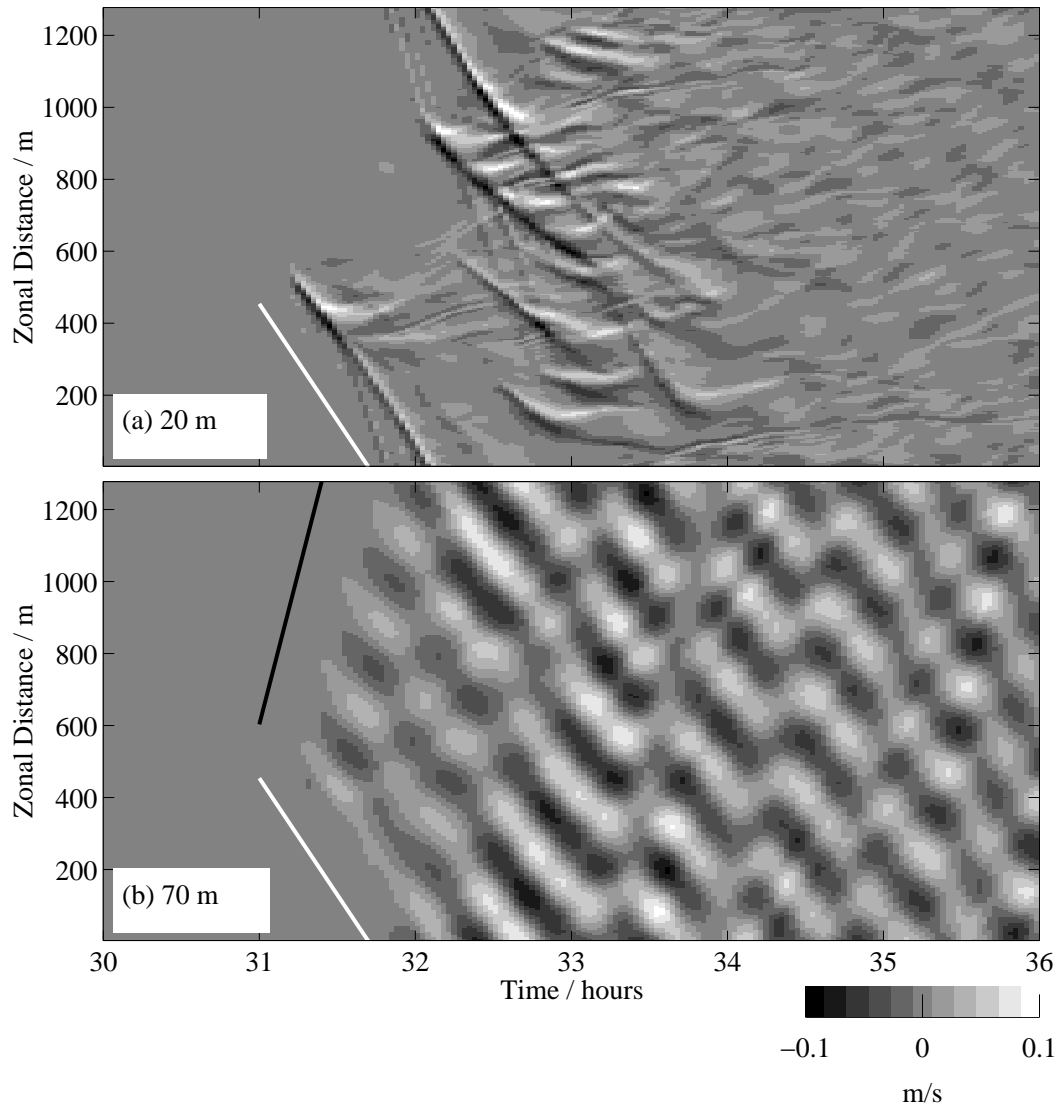


Figure 2. Contours of vertical velocity at 20-m and 70-m depths for the onset of convection and waves at 30–36 hr. The slope of the white lines correspond to the eddy and internal wave propagation velocity; the slope of the black line corresponds to the rate of downstream advection of the waves.

## IMPACT/APPLICATIONS

The generation of internal waves in the equatorial Pacific and the resulting turbulence can be predicted using linear stability theory. Turbulence is initiated by wave-induced shear instability. The use of high-frequency thermistor data to predict turbulence levels has been shown. The technique might be valid for turbulence generated by near-inertial waves through the ocean.

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- Results of Andrew Mack's thesis work can be found at  
[http://micmac.gso.uri.edu/mack\\_thesis](http://micmac.gso.uri.edu/mack_thesis)  
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